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Article

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Evaluating flood, sprinkler and drip irrigation systems for dragon fruit production in Bangladesh

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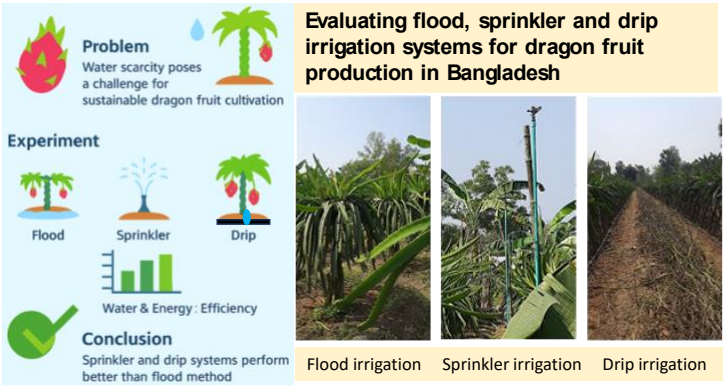

Highlights

- *Dragon fruit is drought-tolerant, but supplemental irrigation is critically important.*
- *Flood irrigation required more water and energy, with the lowest user satisfaction.*
- *Drip irrigation achieved the highest water productivity using minimal water and energy.*
- *Sprinkler systems provided the largest area coverage with high user satisfaction.*
- *All systems achieved payback within a year, with flood and drip recovering faster.*

Abstract

Water scarcity and inefficient irrigation practices are major challenges to sustainable fruit production in Bangladesh. Although dragon fruit (*Hylocereus* spp.) is relatively drought-tolerant, supplemental irrigation is crucial during flowering and fruiting to achieve high yield and fruit quality. In the Madhupur Tract, declining groundwater levels necessitate evaluating modern irrigation systems to promote efficient water use and ensure profitability. This study compared the performance of traditional flood, sprinkler, and drip irrigation systems for sustainable dragon fruit production. The focus was on water and energy use efficiency, productivity, farmer satisfaction, and economic viability (benefit–cost ratio, net present value, and payback period). Twelve dragon fruit farms were selected across the Madhupur Tract, representing each irrigation type. Data were collected on irrigated area, irrigation source, soil type, irrigation depth and interval, energy use, fruit yield and quality, user satisfaction (water distribution uniformity, runoff loss, waterlogging, soil erosion, water saving, and water quality), and installation and operation costs. Sprinkler and drip irrigation systems outperformed the traditional flood irrigation system in nearly all parameters. Drip irrigation delivered the highest irrigation water productivity (6.12 kg/m³) and the top benefit–cost ratio

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(2.08). It also provided water effectively (0.45 cm/event). Sprinkler systems achieved the highest land coverage (1.04 ha) and the best user satisfaction with the lowest energy demand (920 kWh/ha/year). Flood irrigation consumed the most water (2.1 cm/event), required the highest energy (2364 kWh/ha/year), and received the lowest satisfaction ratings. Sprinkler and drip systems delivered superior yields and fruit quality. Although their initial setup costs were higher, all systems achieved payback within a year, with drip and flood systems recovering costs the fastest (0.10 years). Overall, drip and sprinkler systems proved more efficient, profitable, and environmentally sustainable than conventional flood irrigation. The study recommends promoting precision irrigation technologies and providing targeted financial support for sustainable crop production in water-stressed regions.

1 Introduction

Irrigation plays a critical role in global food security. Over 20% of cultivated land worldwide is irrigated, contributing to more than 40% of global food production (World Bank, 2020). Seijger et al. (2025) stated that irrigated systems consistently outperform rainfed agriculture in terms of productivity because they provide controlled water availability, enabling optimal crop growth throughout the growing season. However, the increasing reliance on irrigation has placed immense pressure on water resources, particularly in semi-arid and intensively farmed regions (Fang et al., 2018; Wei et al., 2023; Karandish et al., 2025). Groundwater levels in Dhaka city of Bangladesh are expected to drop by 3–5.1 m/yr by 2030, approximately 70% faster than the current rate, due to excessive extraction (Eco-Business, 2022). This trend is also observed in the Barind Tract of Bangladesh, where groundwater levels have declined at 0.42 m/yr during the wet season and 0.22 m/yr during the dry season, attributed to increased irrigation demands (Monir et al., 2025). Groundwater levels have been declining in the Madhupur Tract of Bangladesh and throughout much of the country in recent years, making it essential to adopt advanced irrigation technologies for effective water management. This issue is particularly pressing in areas facing increasing freshwater scarcity due to climate change, population growth, and competing business needs. Improving irrigation techniques has become a key strategy to enhance water use efficiency, reduce losses, and assure food and nutritional security (FAO, 2020).

Choosing suitable irrigation methods is particularly important for high-value crops, such as dragon fruit (*Hylocereus* spp.). Dragon fruit is gaining popularity in Bangladesh because of its unique appearance, financial gains, health benefits, adaptability, and low maintenance requirements. Area under dragon fruit cultivation in Bangladesh has expanded considerably, reaching ~1460 ha, with an annual production of ~5,959.29 Mt in 2023 (BBS, 2023). Its high nutritional value, including vitamins, dietary fiber, and antioxidants, makes it popular in both domestic and international markets (Hossain et al., 2021; Harshitha et al., 2024). The pH ranges from 4.77 to 5.40, with total soluble solids of 8.0–12% (Arivalagan et al., 2021), moisture content of 82.40–89.98 g/100 g, dietary fiber of 0.97–2.65 g/100 g, carbohydrates of 5.13–12.97 g/100 g, protein content of 0.89–1.45 g/100 g (Arivalagan et al., 2021), vitamin C of 0.025–4.40 mg/100 g, vitamin A of 85.22–890.80 µg/100 g, potassium of 123.00–437.35 mg/100 g, calcium of 1.75–45.00 mg/100 g, and sodium of 14.30–35.63 mg/100 g fresh weight (Nurul and Asmah, 2014; Arivalagan et al., 2021).

Dragon fruit is a drought-tolerant tropical cactus species (Harshitha et al., 2024). Warm tropical climates are ideal for dragon fruit trees. It can withstand humidity and heat. Temperatures between 18°C and 33°C are perfect for Dragon cultivation. Bangladesh has a subtropical monsoon climate, with an annual rainfall of 2030 mm concentrated during the monsoon season (May to October). The country experiences moderately low temperatures in winter (November to March) and high temperatures in summer (April to October). Dragon fruit requires somewhat acidic, well-draining soil (Bozhurin, 2024). Its cultivation is expanding in the Madhupur Tract in Bangladesh, a region characterized by slightly undulating red-brown terrace soils, moderate rainfall, and a distinct microclimate that promotes fruit production (SRDI, 2024). The Madhupur Tract in Bangladesh was selected because its warm tropical climate (20–32°C) and moderate annual rainfall (1,000–1,500 mm) closely match the optimal conditions for dragon fruit cultivation (Amin et al., 2025; Mondol et al., 2025). Its well-drained red-brown terrace soils with slightly acidic pH (5.5–6.5) provide ideal conditions for root growth and nutrient uptake (Chapai et al., 2024; Pandey and Kumar, 2024). Typically, the fruiting season is from April to October, aligning with the monsoon season, which provides the necessary long daylight hours for flowering and fruiting. During this period, the average rainfall ranges between 500 to 1500 mm, supporting the plant's water requirements. However, during the dry months from November to March, water scarcity can occur, necessitating supplemental irrigation (Seijger et al., 2025). Harvesting usually occurs from October to November, when the fruit attains bright coloration and full size. Harvesting is done manually, typically in the early morning to avoid high temperatures (Hossain and Islam, 2022).

Despite its drought tolerance ability, dragon fruit requires supplemental irrigation during rain-less periods, particularly at the flowering and fruit-setting stages, to achieve optimal yield and fruit quality. Inadequate water during these stages can lead to reduced fruit set, bud drop, and the production of misshapen or undersized fruits, thereby compromising both yield and quality (Kakade et al., 2025). Karunakaran et al. (2019) suggested that during peak dry season, when rainfall is absent, irrigation should be applied twice weekly at ~3 L/plant. However, the type of irrigation application can significantly influence overall crop performance and water use efficiency. Therefore,

understanding the water requirements of dragon fruit and the effectiveness of various irrigation techniques is essential for optimizing production (Trivellini, 2020).

In Bangladesh, particularly in Madhupur Tract, conventional flood irrigation has been a prevalent method for dragon fruit cultivation. This approach utilizes both groundwater and surface water sources. Water is often pumped using diesel or electric pumps, with capacities ranging from 1 to 5 horsepower, depending on the orchard size and water availability (Mitra et al., 2021). To address these challenges, modern irrigation systems like drip and sprinkler irrigation are being adopted. These systems offer more efficient water use, reduce labor costs, and minimize water wastage. For instance, in Tangail, farmers have reported a 75% reduction in electricity bills and an 80% decrease in water wastage by switching to sprinkler irrigation. Besides, irrigation tasks that previously took four days can now be completed in 24 hours (The Business Standard, 2024).

The traditional flood irrigation involves applying large amounts of water to fields, allowing it to flow over the soil surface and saturate the crop area, with minimal technological input. Although inexpensive and easy to implement, this method is inefficient due to significant water loss through evaporation, percolation, and surface runoff. Uncontrolled water flow can lead to soil degradation by eroding the topsoil, which decreases soil fertility and increases nutrient leaching. This negatively impacts soil health and crop productivity (Sarker et al., 2019; Cui et al., 2022). In contrast, sprinkler and drip irrigation systems provide better water distribution and conservation. These systems differ significantly in their ability to optimize water use, reduce energy consumption, and enhance productivity, and these factors are becoming increasingly important in areas experiencing water scarcity and climate stress (Cui et al., 2022).

Sprinkler irrigation, where water is sprayed over crops, similar to natural rainfall, using pipes and rotating nozzles, can provide relatively uniform water distribution over extensive areas and is suitable for flat or hilly topographies. It significantly improves water use efficiency compared to flood irrigation and reduces soil erosion. However, it may result in higher evaporation losses and be less effective in windy conditions, and it may incur moderate energy and maintenance costs (Zazueta, 2018). Drip irrigation is a rapidly advancing technology (Zhang et al., 2021). It precisely controls water delivery with a stable discharge, applying it directly to the plant root zone. This method minimizes losses, improves water use efficiency, reduces weed growth, and maintains consistent soil moisture, resulting in better fruit quality and yield. Although it requires a higher initial investment and maintenance, it conserves water, protects soil structure, and lowers long-term labor and water costs. It also helps reduce labor requirements (Sarker et al., 2019).

Sprinkler and drip irrigations can save water compared to flood irrigation by reducing losses from evaporation and deep percolation during water delivery (Sarker et al., 2019). As irrigation water shortages increase, water-saving methods will become more important. However, their widespread adoption remains limited due to high investment and maintenance costs and the lower economic returns of certain crops (Paredes et al., 2014). Savings from reduced water costs in some crops may be insufficient to offset the equipment costs of a drip system. Choosing a suitable irrigation method depends on water availability, crop type, and management needs. Given the importance of water-efficient agriculture and the growing interest in dragon fruit cultivation in Bangladesh, it is essential to evaluate and compare the performance of flood, sprinkler, and drip irrigation systems in terms of water use, crop growth, yield, and cost-effectiveness. This study aims to assess the performance and economic benefits of these irrigation methods and to identify technologies that align with the region's resource availability and sustainability.

2 Materials and methods

2.1 Study site

This study was conducted in 12 dragon fruit gardens in the Madhupur Tract of Bangladesh (**Fig. 1**). The tract is a physiographic region characterized by gently undulating red-brown terrace soils, moderate rainfall, and a distinct agroclimatic zone well-suited for cultivating high-value crops such as dragon fruit (*Hylocereus* spp.) (SRDI, 2024). The area lies within the north-central hydrological region and the Agroecological Zone of the Madhupur Tract. The texture of the old acid soil in the area is clay loam, with lower pH and higher field capacity (**Table 1**). Soil nutrient levels ranged as follows: total nitrogen from 0.07 to 0.16%, available phosphorus from 2.45 to 16.62 ppm, exchangeable potash from 16.09 to 98.41 ppm, and available sulfur from 3.95 to

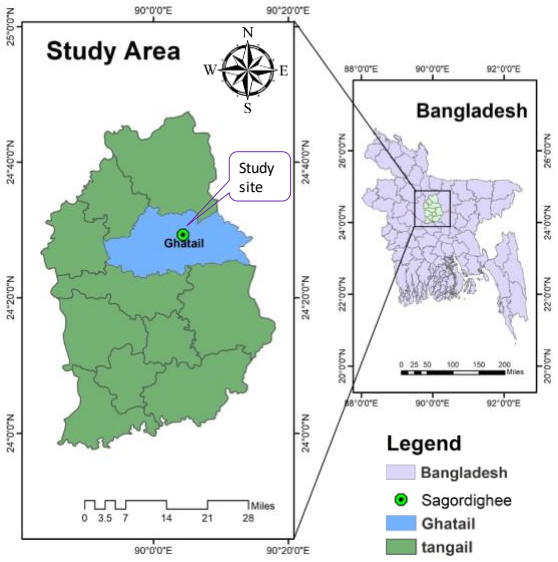

Figure 1. *Map showing the study location in Sagordighee, Ghatail, Tangail.*

27.52 ppm (Ratul et al., 2021). The Madhupur Tract experiences seasonal water scarcity during the dry season (March–April), with peak scarcity and essentially no rainfall in December–February, when irrigation is required (Egashira and Karim, 2001). The region's primary source of irrigation is groundwater, extracted through pumping systems. However, because of over-extraction for agricultural, domestic, and industrial uses, groundwater levels are declining at an alarming rate (Mahmud et al., 2021). Islam et al. (2021) reported that groundwater-level declines at 2.25 m/year in the Upper Dupi Tila aquifer and 2.8 m/year in the Middle Dupi Tila aquifer. In Dhaka city, maximum decline rates range from 4.0 to 5.74 m/year. Liu et al. (2024) found that groundwater storage declines of about -5.5 mm/year nationwide. Given these circumstances, the Madhupur Tract provides a strategic site for comparing traditional flood irrigation with modern alternatives, such as sprinkler and drip irrigation systems.

This region enjoys a wet tropical climate, with an average annual temperature of 29.96°C and monthly average temperatures ranging from 13°C to 33.4°C. The daily maximum temperature from April to May ranges between 32°C and 40°C. Hot and humid summers extend from March to September. Winter (November to February) is milder with occasional rainfall. This area receives an average annual rainfall of 2249 mm (**Fig. 2**) (BMD, 2024). In the study area, the groundwater level peaks in October and then steadily depletes until the beginning of the monsoon in April (Amin et al., 2025).

2.2 Irrigation systems

In this study, flood, sprinkler, and drip irrigation systems were evaluated. Data was collected from 12 dragon fruit gardens that were two years old. The pumping system for all the irrigation systems was the same. Groundwater was pumped using submersible pumps with a capacity of 15 L/s. In the flood irrigation system, water was distributed via open earthen channels, allowing it to flow over the soil surface and crop fields. The sprinkler irrigation system delivered water to fields by spraying droplets through plastic pipes and sprinkler heads (SSS, Tangail, Bangladesh). This system consisted of lateral pipelines ranging from 122 m to 500 m, with nozzles spaced 15 m to 25 m apart, depending on nozzle capacity. Drip irrigation supplied water from a 1000-L overhead tank at low pressure (4 m water head) through plastic tubing equipped with emitters that regulate flow rate (SSS, Tangail, Bangladesh). This method applies water directly to the plant root zone, minimizing water loss from surface runoff or deep percolation and enhancing water productivity (Zhang et al., 2021). Emitter spacing in drip irrigation was determined by plant spacing, which is generally 15 cm. Fertilizer application was consistent across all irrigation systems.

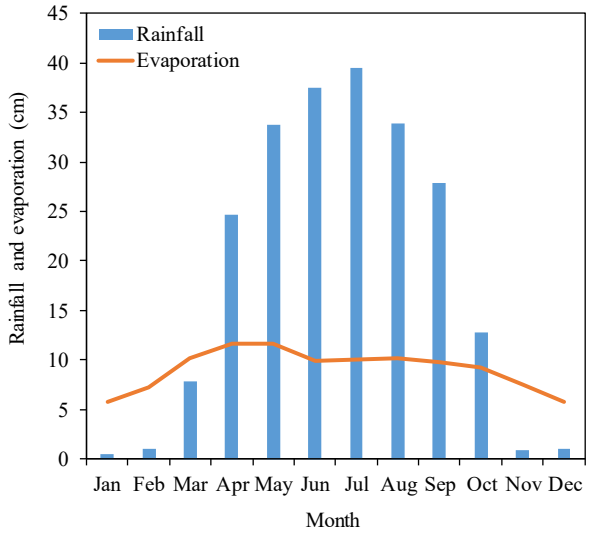

Figure 2. *Monthly rainfall and evaporation rate in the study area (BMD, 2024).*

Table 1. *Physicochemical properties of soils.*

Parameter	Value
Sand (%)	23
Silt (%)	38
Clay (%)	39
Textural class	Clay loam
pH	5.5
Organic matter (%)	1.36
Bulk density (g/cm^3)	1.25
Saturated water content (cm^3/cm^3)	0.49
Field capacity (cm^3/cm^3)	0.42
Saturated conductivity (cm/day)	11

2.3 Data collection

This study selected 12 dragon fruit farms representing flood, sprinkler, and drip irrigation systems. The gardens with the same dragon variety, pumping system, soil types, and management practices were chosen to avoid the background heterogeneity in the study. All the gardens received recommended inputs for their agronomic needs. Therefore, the background information for each garden was not reported in this study. Data on irrigation system dimension, irrigation application (total irrigated area or command area per pumping unit, source of irrigation water, soil type, volume of water, water distribution uniformity across the field, irrigation interval, runoff loss, water logging, soil erosion, availability of water source, water quality), crop quality and yield (yield per unit area, total production per year, plant height, plant growth uniformity, fruit color, and fruit size), installation and operation costs (installation costs, type of energy, energy consumption per irrigation, energy costs, and other operation costs) and other relevant information were collected from the logbooks of the selected farmers. Whether farmers were satisfied or not satisfied on selected performance indicators of the irrigation systems (distribution uniformity, runoff occurrence, water

logging, soil erosion, water quality, sedimentation, and water saving) was quantified.

2.4 Economic and financial analysis

Economic and financial analyses were conducted to assess the profitability and feasibility of different irrigation systems for dragon fruit production in the Madhupur Tract. The analyses included the estimation of fixed cost, variable cost, benefit–cost ratio (BCR), and payback period following standard farm management and economic evaluation procedures (Gittinger, 1982; FAO, 2017; Rahman et al., 2020).

2.4.1 Fixed and variable costs

The fixed cost (FC) represents expenses that remain constant regardless of production level, such as land rent, depreciation of irrigation equipment, interest on capital, and machinery cost.

$$FC = \sum_{i=1}^{n} C(\text{fi}) \quad (1)$$

where C(fi) denotes individual fixed cost components (e.g., equipment, infrastructure, and land).

The variable cost (VC) includes costs that vary with production scale, such as labor, fertilizer, irrigation water, fuel, electricity, and maintenance.

$$FC = \sum_{j=1}^{m} C(\text{vj}) \quad (2)$$

Total production cost (TC) was obtained by summing fixed and variable costs.

$$TC = FC + VC \quad (3)$$

2.4.2 Gross return and net return

Gross return (GR) was calculated as the total revenue from crop yield multiplied by the market price:

$$GR = Y * P \quad (4)$$

where (Y) is the yield (kg/ha) and (P) is the prevailing market price (BDT/kg).

Net return (NR) was determined by deducting total cost from gross return:

$$NR = GR - TC \quad (5)$$

2.4.3 Benefit–cost ratio

The BCR was used to evaluate the economic efficiency of each irrigation system and was computed as the ratio of gross return to total cost:

$$BCR = \frac{GR}{TC} \quad (6)$$

A BCR > 1 indicates economic viability, whereas a BCR < 1 suggests that production is not profitable (CIMMYT, 1988; Alam et al., 2022).

2.4.4 Payback period

The payback period (PBP) estimates the time required to recover the initial investment from the annual net returns. It was calculated as:

$$PBP = \frac{I}{NR} \quad (7)$$

where I is the total initial investment (BDT/ha). A shorter payback period reflects a faster recovery of capital and a more economically attractive option (Gittinger, 1982; Rahman et al., 2020).

A discount rate of 10% was applied to calculate the net present value (NPV), benefit-cost ratio (BCR), and payback period for dragon fruit production systems. This rate represents the minimum acceptable return that investors or farmers expect from their project investments, ensuring that future cash flows are appropriately discounted to their present value (Gittinger, 1982; FAO, 2017).

2.5 Data analysis

Irrigation depth was calculated by dividing the volume of water applied by the irrigated area. Irrigation water productivity was determined according to Mahbub et al. (2023), defined as the crop yield divided by the total irrigation water applied. Farmers' satisfaction with each irrigation system was expressed as a percentage. Data were analyzed using one-way analysis of variance in Microsoft Excel 2016, and treatment means were compared using the least significant difference at a 5% significance level.

3 Results

3.1 Irrigation command area and water sources

Irrigation command areas under different irrigation systems varied considerably (**Fig. 3**). The sprinkler irrigation system (1.04 ha) had a larger command area than the flood and drip irrigation systems (0.45 ha). Higher sprinkler system efficiency may have helped cover a larger command area than

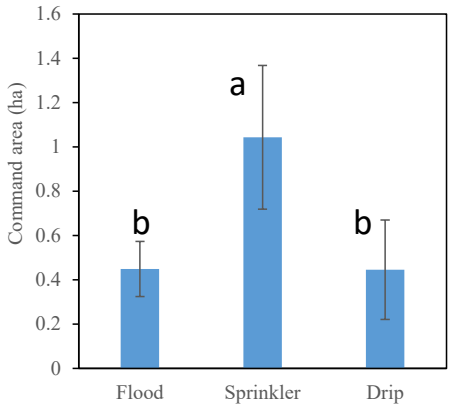

Figure 3. *Total command area under different irrigation systems. The values are not significantly different when followed by the same lowercase letter (a, b, and c) at a level of p < 0.1 and n = 4.*

the flood irrigation system. The command area also depends on operating hours and available irrigable land in the adjacent area. Besides, the owners of the larger-sized farms wanted to invest in sprinkler irrigation technology. The low command area under the drip irrigation system did not reflect its efficiency. This system had the highest irrigation water productivity. This system is still not widely adopted in this area due to users' perceptions of high initial costs, operational difficulties, the burden of constructing overhead tanks, and emitter clogging. During field observations, it was revealed that the rain-like water application of the sprinkler system was more popular. Many farmers believe that rain-like irrigation removes dust from plant leaves and lowers the ambient temperature, which can enhance plant growth, flowering, and fruiting. Groundwater is used for irrigation in all the systems. There is no alternative dependable water source in this location to divert for irrigation.

3.2 Irrigation depth and interval

Irrigation depth per event varied substantially among the three irrigation systems. As shown in **Fig. 4a**, flood irrigation delivered an average depth of 2.55 cm per event, whereas sprinkler and drip systems applied only 1.13 cm and 0.45 cm, respectively, to reach the target soil water level set by farmers' perception. The root system of dragon-fruit is very shallow, typically distributed in the top 15–30 cm of soil, and annual water requirement estimates of ~120–150 cm/year under favorable conditions (Kakade et al., 2023).

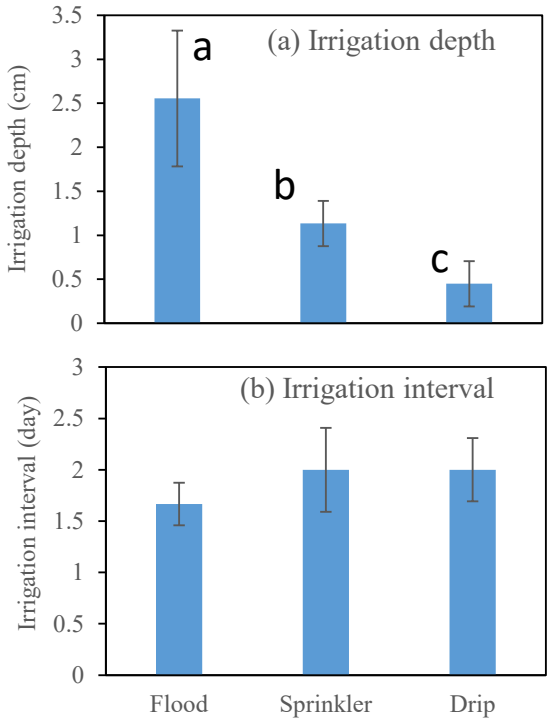

Figure 4. *Irrigation depth per irrigation event and irrigation interval under different irrigation systems. The values are not significantly different when followed by the same lowercase letter (a, b, and c) at a level of $p < 0.1$ and $n = 4$.*

Table 2. *Users' satisfaction level (%) on performance indicators of the flood, sprinkler, and drip irrigation systems.*

Parameter	Flood	Sprinkler	Drip
Distribution uniformity	50	100	100
Runoff occurrence	25	100	100
Water logging	25	100	100
Soil erosion	25	100	100
Water quality	100	100	100
Sedimentation	100	100	100
Water saving	75	100	100

The greater depth required by flood irrigation reflects conveyance and field losses, including seepage, deep percolation, and surface evaporation, as well as limited control over the exact volume applied.

The irrigation interval did not vary significantly for the irrigation systems (**Fig. 4b**). Under the flood irrigation system, irrigation was applied at 1.7-day intervals, while the sprinkler and drip systems irrigated the gardens at 2-day intervals. The results indicate that the flood irrigation system was less effective than the sprinkler and drip systems due to its higher water losses and uneven water distribution. For small grain crops, irrigation is typically applied at 1- to 2-week intervals to maintain an optimal soil water reserve that meets the crop's water demands. In contrast, these fruit plants required more frequent irrigation to minimize heat stress and ensure safe fruit development.

3.3 Users' satisfaction

User satisfaction assessments of flood, sprinkler, and drip irrigation systems show that farmers' understanding of operational features varies significantly (**Table 2**). Drip and sprinkler systems received full satisfaction ratings (100%) for distribution uniformity, water quality, water-saving, and soil erosion reduction. Flood irrigation had much lower satisfaction, with distribution uniformity reaching only half the satisfaction level, and combined scores for runoff, waterlogging, and erosion at just 25%. Results indicate that 75% of farmers believe flood irrigation causes runoff loss, waterlogging, and soil erosion. Farmers reported no concerns about water quality or sedimentation across the irrigation systems. Approximately 25% of farmers believe that sprinkler and drip systems save water compared with flood irrigation. Low-voltage electricity can sometimes affect sprinkler system performance. Overall, data indicate that sprinkler and drip irrigation systems operate efficiently across various areas. In contrast, traditional flood irrigation systems display low efficiency and require updates to align with precision agriculture standards for sustainable resource conservation.

3.4 Energy consumption and installation costs

Energy consumption varied among the irrigation methods, which can significantly affect the sustainability of these

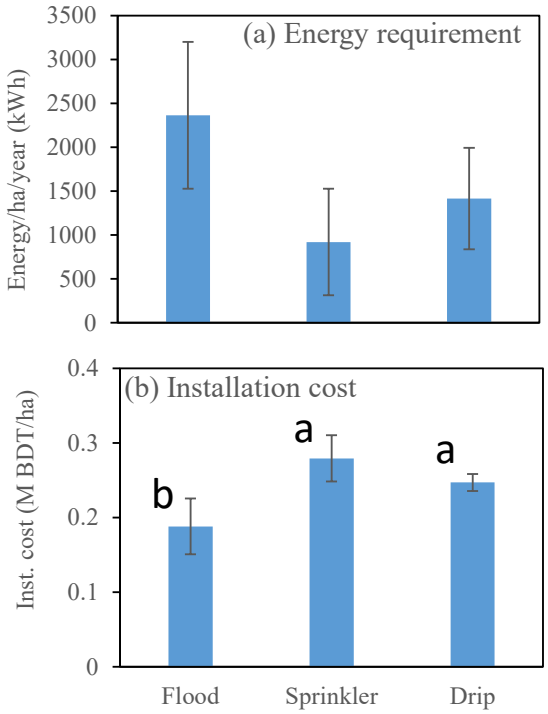

Figure 5. *Energy requirement per irrigation event (a) and installation costs (b) for different irrigation systems. The values are not significantly different when followed by the same lowercase letter (a, b, and c) at a level of p < 0.1 and n = 4.*

farming practices (**Fig. 5a**). Flood irrigation was energy-intensive, requiring 2465 kWh/ha/year, compared with the other two systems. The high energy consumption of flood irrigation is mainly due to the large amount of water transported and distributed across the fields. Drip irrigation exhibited a medium energy requirement, needing 1415 kWh/ha/year. The higher efficiency of this method can be attributed to its precision in delivering water directly to the plant root zone, minimizing both energy expenditure and water wastage. The adoption of drip irrigation not only supports energy conservation but also promotes sustainable water management practices. For the drip irrigation system in this study, water was pumped to an overhead tank and subsequently distributed through gravity-fed drip irrigation tubes. In this study, the sprinkler risers of 3 m height were connected directly to the pump delivery pipe, which minimized energy losses. The riser height (3 m) was much lower than the total pumping head (~20 m), and the system had no big guns or traveling guns for long-distance application. As a result, the sprinkler system consumed relatively lower energy (about 920 kWh/ha/year). Compared with flood irrigation, sprinklers distribute water more evenly and apply it closer to the crop canopy, reducing water loss and improving application efficiency. Sprinkler irrigation, however, usually requires more energy than drip or surface (flood) systems because it operates at higher pressure to spray water across the field. The higher energy used in the flood irrigation system is mainly due to the larger volume of water that must be moved and distributed.

The flood, sprinkler, and drip irrigation systems had different installation costs (**Fig. 5b**), and this factor is crucial in determining the economic sustainability of the methods. Installation costs are the lowest (0.18 M BDT/ha) for flood irrigation. This affordability makes flood irrigation an attractive option for farmers with limited upfront capital. The installation cost of sprinkler irrigation was the highest at 0.28 M BDT/ha, indicating the complexity of its installation. For the installation of the drip irrigation system, the total cost was 0.26 M BDT/ha, placing it between flood and sprinkler systems.

3.5 Fruit yield and water productivity

The sprinkler and drip irrigation systems produced higher yields than flood irrigation (**Fig. 6a**). However, the irrigation systems did not affect the plant height. The growth and yield of the plants were inconsistent across the same plot. The uneven growth and yield can be attributed to the heterogeneity of soil fertility and water availability, or a lack of appropriate management across the fields. Farmers were generally satisfied with the color under all the irrigation systems. The fruits' size under the sprinkler and drip irrigation systems was satisfactory. For the flood irrigation system, some (25%) farmers experienced a smaller size of the fruits. Some plants under the flood irrigation system wilted during peak sun time.

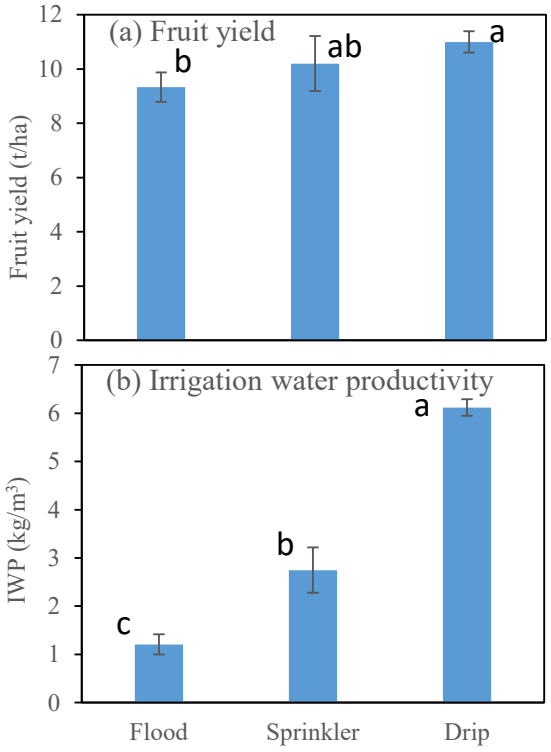

Figure 6. *Fruit yield (a) and irrigation water productivity (b) of dragon fruits under different irrigation systems. The values are not significantly different when followed by the same lowercase letter (a, b, and c) at a level of p < 0.1 and n = 4.*

Table 3. *Economic indicators for three irrigation systems estimated at 10% discount rate over 20-year period.*

Irrigation system	NPV (BDT)	BCR	Payback Period (yrs)
Flood	7914884	2.00	0.10
Sprinkler	9090245	2.05	0.13
Drip	12285933	2.08	0.10

The drip irrigation system showed the highest irrigation water productivity (6.12 kg/m^3), followed by the sprinkler (2.75 kg/m^3) and flood irrigation system (1.21 kg/m^3) (**Fig. 6b**). The lowest irrigation needed, and the highest yield obtained under the drip irrigation system resulted in the highest irrigation water productivity. The increase in irrigation water productivity reflects the reduced water losses (soil evaporation, runoff, and percolation) and improved grain yield.

3.6 Cost-benefit analysis and payback period

The water productivity approach alone is insufficient for identifying the optimal irrigation method. Economic profitability must also be evaluated. The revenue of growers is directly impacted by the prices of agricultural products. Results of the analysis, including Net Present Value (NPV), Benefit-Cost Ratio (BCR), and Payback Period, are presented in **Table 3**. Flood irrigation exhibited the lowest installation cost (BDT 0.18 M/ha). The sprinkler and drip systems required higher initial investments of BDT 0.28 M/ha and BDT 0.26 M/ha, respectively (**Fig. 5b**). Operational energy costs were lowest for the drip system at 18 kWh per event, which contributes to its economic advantage by reducing ongoing expenditures (**Fig. 5a**). The economic evaluation of flood, sprinkler, and drip irrigation systems indicated only minor differences in profitability and investment efficiency (**Table 3**).

Drip irrigation emerged as the most economically efficient option with the highest BCR of 2.08, followed closely by the sprinkler system (BCR = 2.05) and flood irrigation system (BCR = 2). These values indicate that for every unit of investment, the drip system returns BDT 2.08, compared with BDT 2.05 and BDT 2.00 from sprinkler and flood systems, respectively. A BCR above 1.0 for all systems confirms economic viability; however, drip irrigation provided the highest return per unit cost, reflecting its efficient water use and higher yield performance (12.62 t/ha) compared to flood (8.47 t/ha) and sprinkler systems (9.48 t/ha).

The NPV values, representing the cumulative present value of net benefits, further confirmed the superiority of drip irrigation (BDT 12.29 M), followed by sprinkler (BDT 9.09 M) and flood (BDT 7.91 M) systems. The higher NPV of drip irrigation underscores its long-term economic feasibility, which justifies its higher initial installation costs.

All irrigation systems demonstrated exceptionally short payback periods, with both drip and flood systems recouping their investments within 0.10 years, and the sprinkler system slightly behind at 0.13 years. Such short return periods indicate profitability and the importance of supplemental irrigation in dragon fruit production.

4 Discussion

This study is the first in Bangladesh to comprehensively compare flood, sprinkler, and drip irrigation systems for dragon fruit production in the Madhupur Tract, a region facing groundwater depletion. Previous research mainly focused on field crops such as rice and wheat (Fang et al., 2018; Mahmud et al., 2021; Mahbub et al., 2023). By including energy use, payback period, and farmer perceptions alongside water productivity, the study offers a more holistic assessment than earlier irrigation comparisons (Sarker et al., 2019; Zhang et al., 2021). To address the water scarcity in the region, it is crucial to use irrigation water efficiently through state-of-the-art technologies (Parvin et al., 2019; Mahmud et al., 2021). Given the documented benefits of sprinkler irrigation, farming communities have adopted sprinkler and drip irrigation systems as alternatives to address the low application efficiency of flooding irrigation systems (Chaudhary et al., 2024). However, the command area under various irrigation systems in the study area generally remains low due to higher water losses and other management problems (BADC, 2024). Reducing irrigation water loss thus permits the expansion of the irrigation command area (Du et al., 2015). This is evidenced by the observation that the sprinkler irrigation system had a larger command area than both flood and drip irrigation systems, indicating its higher efficiency (**Fig. 3**). The drip system had a lower command area than the sprinkler system in this study. However, it has high potential to cover a larger command area due to its higher efficiency. Jensen et al. (2014) stated that drip irrigation minimizes conveyance losses, saving 30–40% of water compared with flood irrigation.

The greater irrigation depth required by flood irrigation reflects significant conveyance and field losses, seepage, deep percolation, and surface evaporation, along with limited control over the applied volume (Fang et al., 2018). Jha et al. (2019) found that the irrigation requirement for winter wheat was 293 mm under flood irrigation compared with 196 mm under a sprinkler system. Additionally, the shallow wetting fronts produced by sprinkler and drip methods align moisture with the densest root zone region, enhancing water uptake efficiency. Conversely, flood systems can exacerbate percolation losses near the inlet and runoff at the

tail end (Sarker et al., 2019). Within flood irrigation systems, a portion of irrigation return flow percolates through the vadose zone and joins groundwater, whereas drip irrigation retards this process (Wang et al., 2018; Rahman and Amin, 2023). Consistent with this, Zhang et al. (2021) found that an estimated 44.9–58.9 mm of irrigation water joined groundwater via deep percolation under flood irrigation.

In addition to meeting the evapotranspiration demand, irrigation can also create a favorable environment for plant growth. In this study, the dragon plants needed regular irrigation to reduce heat stress and ensure safe fruiting. Supporting this approach, previous studies suggest that frequent irrigation application of small quantities can increase crop growth and yield (Bian et al., 2016) as well as water use efficiency. Drip irrigation is more conducive to producing higher crop yields under potential drought stress. Drip irrigation can improve water and nutritional status in the root zone and accelerate plant growth and yield (Fan et al., 2017). In contrast, the air temperature and vapor pressure deficit in the sprinkler-irrigated field were lower than those found in the flood-irrigated field (Liu and Kang, 2006). The farmers under the sprinkler irrigation system reported that the rain-like water application reduced common fungal diseases. Narendra et al. (2021) reported that the crop yield obtained under drip irrigation was the highest, followed by sprinkler and flood irrigation.

Drip irrigation delivered the highest water productivity at 6.12 kg/m³, compared with 2.75 kg/m³ for sprinkler and 1.21 kg/m³ for flood irrigation (**Fig. 6**). The lowest irrigation applied, and the highest yield obtained under the drip irrigation system resulted in the highest irrigation water productivity. Fang et al. (2018) reported that using drip irrigation to double the irrigation application frequency improved yield by 12% and water use efficiency by 20% compared with a single irrigation application using the flooding method. Islam et al. (2017) found comparable irrigation water productivity values for Malta (1.67 kg/m^3), Lichi (1.39 kg/m^3), and Mango (1.64 kg/m^3) under a flood irrigation system in the same climate zone. Jha et al. (2019) found irrigation water productivity of 6.17 kg/m^3 under drip irrigation, 5.8 kg/m^3 under sprinkler irrigation, and 2.33 kg/m^3 under flood irrigation. Narendra et al. (2021) reported similar results, i.e., drip irrigation had the highest irrigation water productivity, followed by sprinkler and flood irrigation. The increase in irrigation water productivity reflects the reduced water losses and improved grain yield.

Quantification of water productivity alone is insufficient to identify the optimal irrigation method (Fernandez et al., 2020). Therefore, cost-benefit analyses of the irrigation systems were performed. Drip irrigation led with a BCR of 2.08, followed by sprinkler at 2.05, and flood irrigation at 2.00 (**Table 3**). Flood irrigation, which relies on gravity, requires lower energy costs for water distribution (Shankar et al., 2015). Fang et al. (2018) reported that the drip irrigation system had the highest costs, followed by the sprinkler and flood irrigation systems. Narendra et al. (2021) found that the costs of cultivation using sprinkler irrigation were higher than those associated with drip and flood irrigation, and the net returns from drip irrigation were greater than those from both sprinkler and flood irrigation. The differences in BCR and NPV are consistent with prior research, emphasizing the positive impacts of precision irrigation on productivity and profitability (e.g., Sarker et al., 2019). This finding aligns with previous studies suggesting that high-return horticultural crops can justify the adoption of costly but efficient irrigation technologies (Muslim et al., 2018). These results indicate that while traditional flood irrigation may be easier to adopt because of lower upfront costs, the long-term financial, agronomic, and environmental benefits of drip and sprinkler systems make them superior choices for sustainable fruit production. In addition, a rainwater harvesting system can enhance this fruit-farming system, as suggested by Islam et al. (2017). These interventions align well with irrigation and agricultural water management national policies (WARPO, 2025). Farmers' adoption rate of these technologies is gradually increasing in Bangladesh (BADC, 2024).

5 Conclusion

The comparative evaluation of flood, sprinkler, and drip irrigation systems for dragon fruit cultivation in the Madhupur Tract reveals significant differences in terms of water use efficiency, energy consumption, user satisfaction, and crop yield. While flood irrigation remains the most affordable in terms of installation cost, it is associated with higher water losses, greater energy demand, and lower user satisfaction. Conversely, sprinkler and drip irrigation systems demonstrated superior performance across all major indicators. Drip irrigation exhibited the highest yield, efficiency in water and energy use, and minimal erosion and waterlogging. While the initial investment for modern systems is higher, their long-term benefits, including increased yield and resource conservation, clearly justify the costs. The comparative cost-benefit analysis of flood, sprinkler, and drip irrigation systems for dragon fruit production in the Madhupur Tract demonstrates that modern irrigation technologies, especially drip irrigation, offer superior economic and agronomic performance. Despite the higher initial investment, drip irrigation produced the highest BCR (2.08), greatest NPV (BDT 12.29 million), and shortest payback period (0.10 years), outperforming both sprinkler and flood systems. The sprinkler system also showed strong economic returns, making it a viable alternative where the drip system is not feasible. These findings highlight the potential of precision irrigation technologies to promote sustainable horticultural production, especially for high-value crops like dragon fruit in water-stressed regions. The study recommends three key policy interventions: (i) the provision of targeted subsidies or concessional loans to alleviate smallholders' installation costs; (ii) the promotion and dissemination of intuitive irrigation-scheduling tools to optimize crop yield while minimizing water losses, nutrient leaching, and soil erosion; and (iii) the establishment of a comprehensive groundwater-

monitoring framework to safeguard aquifer sustainability and guide adaptive irrigation decision making.

6 Data availability statement

The supplementary data, including raw data files and code used for analysis, are available upon request from the corresponding author.

7 Ethical statements

This study does not involve human or animal subjects. Ethical approval was not required for this research. All data used were publicly available or obtained through proper channels, with consent where applicable.

8 Conflict of interest

The authors declare no conflict of interest related to this study.

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10 Author contributions

M.G.M. Amin, SSRMMA Sorwar, MRI Mondal, PK Sarker, and M.H. Rahman conceptualized the study. M.G.M. Amin, U.S. Shammy, and M.A. Rouf conducted the data analysis and wrote the manuscript. SSRMMA Sorwar, MRI Mondal, PK Sarker and M.H. Rahman assisted with the data collection and interpretation of results. All authors approved the final version of the manuscript

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